Control of electric field domain formation in multiquantum well structures

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The formation, expansion, and readjustment of electric field domains in multiquantum well stacks is described and explained in terms of sequential resonant tunneling. These effects are used to control the multiband spectral response in IR detector applications of these structures.

The formation of electric field domains (EFD) was first observed in bulk GaAs and is mostly known as the cause of Gunn oscillations.[1] It is explained in terms of the negative differential resistance (NDR) which occurs because of the electron transfer from the Γ to the X or L valleys. Esaki and Chang[2] first observed the formation of static EFDs in multiquantum wells (MQW); this phenomenon was attributed to the NDR which arises due to sequential resonant tunneling (SRT) between subbands in adjacent wells.[3–6]

Recently, we demonstrated the operation of a tunable quantum well infrared detector which was based on the formation of EFDs in a MQW device.[7] In this letter, we report on an investigation designed to determine the parameters which govern EFD formation and expansion. We show theoretically and experimentally how the proper choice of well widths, heights, and doping determines the electric field domain profile.

First, we discuss EFDs in the three-stack MQW device presented in Ref. 7. In this device the superlattice clad by two n-doped contact layers, consisted of three stacks of 25 QW each; the first 25 wells were 3.9 nm wide and were separated by $Al_xGa_{1-x}As$ ($x=0.38$) barriers; the second stack consisted of 4.4 nm wide wells with ($x=0.3$) barriers; the last stack had 5.0 nm wide wells and ($x=0.24$) barriers. All the barriers were 44 nm wide; the wells and the contacts were uniformly doped with Si to $n=4\times10^{18}$ cm^{-3}.

The absorption spectrum at room temperature shows three peaks at 1364, 1080, and 920 cm^{-1} obeying intersubband selection rules for the polarization of the incident light.[7] Figure 1 displays the smoothed photocurrent spectral response of a mesa structure, 200 μm in diameter at 7 K, for different values of the applied voltage. The polarity is defined in Fig. 2. We see that at different ranges of applied bias, only some of the peaks in the photocurrent are present. This was explained by the formation of high and low electric field domains in the device. The light is absorbed in all three stacks of QWs but only photoexcited carriers which are in a region with high electric field can be swept out of the QW and contribute to the current. Those in the low field region have a high probability of being recaptured by their own well, contributing only negligibly to the current.

A second indication of the presence of EFDs in the device comes from dark current measurements. A fine structure in the plateaus of the I-V curve, corresponds to regions of NDR.[7] This is due to SRT, which occurs whenever the ground level of a well is aligned with the excited level of the adjacent well.[4] Under an arbitrary applied bias, a uniform distribution of electric field is not stable because all of the QWs will be out of resonance, i.e., none of the energy levels of pairs of adjacent wells will be aligned. Instead, the system will settle into a different configuration in which the electric field profile includes high and low field regions. In the high field region we have ground level to excited level SRT, and in the low electric field region ground level to ground level SRT. Transport within each domain is resonant, while at the boundary between the two regions it is generally nonresonant. This boundary then acts as a bottleneck that limits the current. There should

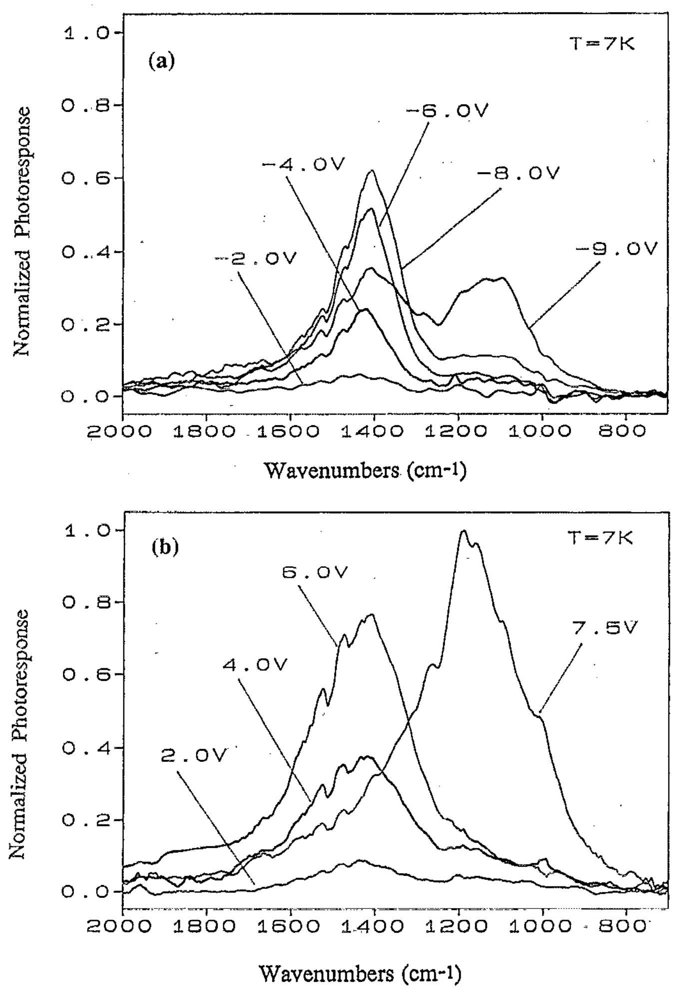

FIG. 1. (a) Spectral photoresponse for a few values of applied negative voltage for the three-stack quantum well device. (b) Spectral photoresponse for a few values of applied positive voltage.

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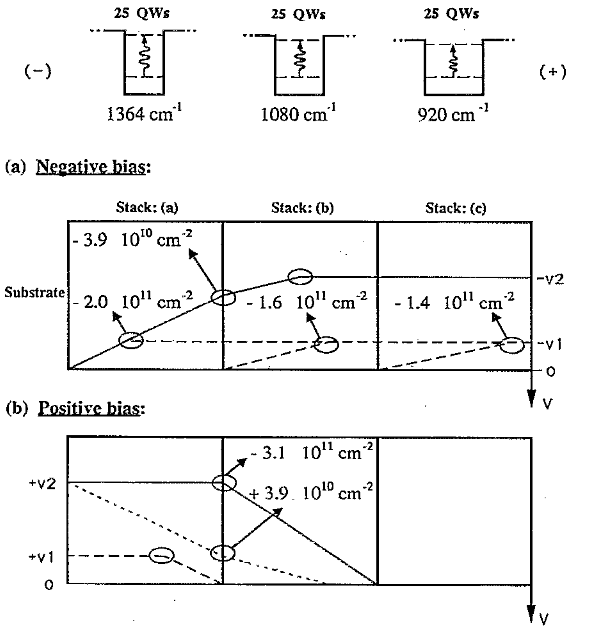

FIG. 2. Voltage drop across the three stacks of quantum wells at negative (a) and positive (b) biases. There is formation of high and low field domains in the MQWs. Note the amount of charge accumulation or depletion at the boundaries where the slope of electric field changes.

also be some charge accumulation or depletion at this boundary because of the change in the slope of electric fields, as required by Poisson's equation. This also has to be considered when determining the current flow through the structure. An increase in the bias will cause more QWs to enter the high field domain (HFD) region, and this is reflected by the oscillatory behavior in the I-V curve.

In the case of our sample, several electric field distributions across the three stacks of QWs are possible [Fig. 2(a) shows four possible distributions for applied biases -$V1$ and -$V2$]. Some of these have only high field domain (HFD) in one of the stacks and others have a combination of HFDs and LFDs (low field domains) in all the stacks. The main rule used to determine different field profiles across the structure is that we may use only the electric field values which result in alignment of energy levels between adjacent wells. In addition the total voltage drop must equal the applied voltage. This results in a large number of possible configurations. The actual electric field distribution should satisfy self-consistently Poisson's equation and the equation of current continuity along the superlattice. Because of the complexity of the transport calculations in MQWs a detailed study, which should also include a stability analysis, is very complicated. In this letter, instead, we try to extract some of the parameters which are important for HFD formation, and use them to design samples with a desired electric field distribution.

One of the important parameters is the amount of charge accumulation or depletion at the boundaries, where the slope of the electric field changes. This charge, by altering the tunneling process (resonant or nonresonant) at that boundary, can limit the total current which flows through the structure. If the transport at the boundary is resonant, the LFD will limit the current and its presence should be considered to estimate the current.

For example at low negative biases [Fig. 2(a), bias -$V1$], considering that different electric fields are needed in the different stacks for the ground level of a well to be aligned with its neighboring well's excited state, we see that a HFD in stack (a) would lead to a charge accumulation of 2.0×10^{11} electrons/cm^2 at the boundary between HFD and LFD, while HFD in the stacks (b) or (c) would require 1.6×10^{11} or 1.4×10^{11} electrons/cm^2, respectively, at the corresponding boundaries. The QWs are doped to 2×10^{12} cm^{-2}, so providing these amounts of charge would not be a limiting process in EFD formation. The barriers in all three stacks being identical, if the current is limited by the domain boundary, one would expect that the configuration in which there is a HFD in stack (a) accommodates more current than the other two configurations, and will probably be more stable. At low positive biases [Fig. 2(b) bias + $V1$] we see again, and at the first sight surprisingly, HFD formation in stack (a). This shows that the screening effect[4] which would cause the domain formation to start from the anode and then expand toward the cathode is not the dominant effect here.

The high field domain switching at +6.5 V and expansion at −8.5 V (Fig. 1) can also be explained in terms of the charges at the boundaries. At high biases, when the HFD would expand to more than one stack, the charge accumulations or depletion at the boundary between two stacks, can limit the current in the structure. This charge is due to the difference between the values of HFD electric fields in different stacks. As can be seen from Fig. 2(a) (bias − $V2$), in the case of negative bias the presence of HFD in both stacks (a) and (b) results in a charge accumulation of 3.9×10^{10} cm^{-2}. In the case of positive bias instead, the same configuration would result in a charge depletion of the same amount at the boundary between the two stacks [Fig. 2(b)]. This charge depletion can reduce the current through the whole device and thus other configurations become more favorable. Eventually, the configuration observed in the experiment for high positive bias incorporates HFD only in stack (b).

As was mentioned earlier, sequential resonant tunneling is the origin of NDR and subsequent EFD formation in the device. The large switching voltage of 6.5 V across 25 periods as observed, corresponds to 260 meV/period. This is much larger than the excited state-ground state separation (E_2-E_1) of 169 meV as inferred from absorption measurements. This indicates a nonzero voltage drop across the low electric field domain region (in agreement with a nonzero linewidth of the subband) or at space charge regions. More importantly, it also shows that the transport might rely on SRT between the ground state and some excited states which are located higher in the continuum, above the top of the well. The very long barriers of 44 nm in this sample and the proximity of the first excited state to the top of the well, can cause the system to "choose" a configuration in which there is SRT through high continuum states (since these states "see" a lower effective barrier). Another interesting point to note is the

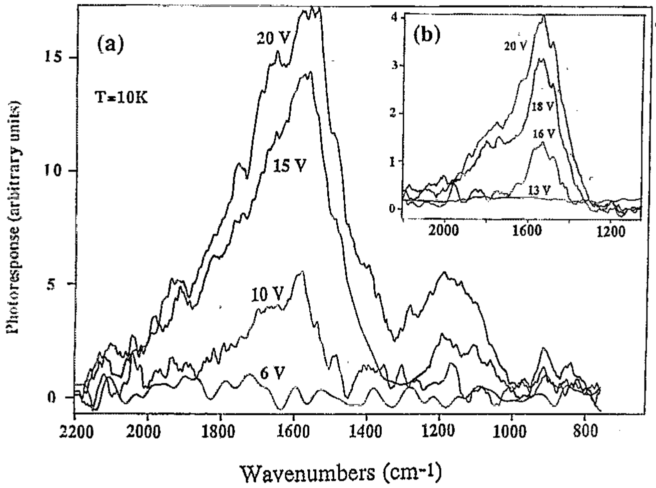

FIG. 3. (a) Spectral photoresponse for the two-stack MQW device and 44 nm barriers in both stacks. (b) (inset) Spectral photoresponse of another two-stack MQW device with similar well characteristics but the barriers in the long wavelength stack are shortened to 20 nm.

reduction in the strength of the high energy peak in the photocurrent measurement at the negative bias of -8.5 V, when the second peak appears (see Fig. 1). This can be explained by a rearrangement of the HFD in the stack (a), in such a way that SRT to lower states in the continuum occurs. From an analysis of the peak strengths at different voltages, one can see that this configuration corresponds to a voltage drop across the stack (a) of ≈ 4 V or 160 meV/period, which is the separation between the ground state and the first excited subband.

Even though there are a lot of processes and parameters which can influence the transport in the superlattice, such as impurity or phonon-assisted tunneling, resonant tunneling through different states in the continuum, relaxation times, and space charge effects; it is still possible to design samples with the desired EFD configuration for applications like tunable infrared detectors. This is done by considering the charge accumulation effects as was discussed earlier. Figure 3(a) shows the photocurrent spectroscopy at different applied biases for a two-stack MQW IR detector with a design similar to that of our original three-stack device. [Stack (a): 4.0 nm GaAs wells separated by 44 nm $Al_{0.36}Ga_{0.64}As$ barriers. Stack (b): 5.2 nm GaAs wells separated by 44 nm $Al_{0.24}Ga_{0.76}As$ barriers.] At low bias there is a peak at short wavelengths ≈ 1600 cm^{-1} and as we increase the applied bias another peak at longer wavelengths ≈ 1200 cm^{-1} appears. As a test vehicle for our formalism we set out to design a two-stack MQW detector which displays the opposite pattern in the photocurrent, i.e., a detector with a long wavelength peak at low bias voltages, with an added short wavelength peak contributing to the photocurrent at higher bias voltages. To achieve this goal, we have to modify the pattern of EFD formation. This was done by reducing the width of the barriers in one of the stacks. This increases the value of the electric field in the high field domain of that stack (it takes a larger field to align the $n=1$ and $n=2$ levels of neighboring wells); and subsequently increases the accumulated charge at the boundary between the HFD and LFD.

Figure 3(b) displays the photocurrent of a second two-stack MQW detector where the barriers in the stack (b) (having absorption peak at longer wavelength) were shortened to 20 nm. [Stack (a): 4.0 nm GaAs wells separated by 44 nm $Al_{0.38}Ga_{0.62}As$ barriers. Stack (b): 4.7 nm GaAs wells separated by 20 nm $Al_{0.30}Ga_{0.70}As$ barriers.] By this mean we can achieve the requirement that the electric field for ground state to excited state SRT be increased in stack (b) and become larger than the corresponding value of the electric field in stack (a). As a result we see that this time the peak at the longer wavelength appears first, and then, by increasing the bias further, the peak at the shorter wavelength appears. It is interesting to note that the spectral photoresponse of these two-stack MQW devices has a similar behavior when we reverse the polarity of the applied bias (not shown in the figure); this is in contrast with the switching behavior observed in the three-stack MQW device. This shows the importance of the LFD in the third stack as a current limiting process. A more detailed analysis of the transport in these devices, considering bound to continuum SRT, is beyond the scope of this letter and will be presented separately.

In conclusion, we have discussed some of the important parameters governing the formation, expansion, and readjustment of electric field domains in multiquantum well structures. For the first time, we showed how the pattern of electric field domain formation can be manipulated by careful design of the device.

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